

Final Report

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Observational and Modeling Studies of Clouds and the Hydrological Cycle

Richard C. J. Somerville, Principal Investigator

1. Summary and Overview

Our approach involved validating parameterizations directly against measurements from field programs, and using this validation to tune existing parameterizations and to guide the development of new ones. We have used a single-column model (SCM) to make the link between observations and parameterizations of clouds, including explicit cloud microphysics (e.g., prognostic cloud liquid water used to determine cloud radiative properties). Surface and satellite radiation measurements were used to provide an initial evaluation of the performance of the different parameterizations. The results of this evaluation will then be used to develop improved cloud and cloud-radiation schemes, which were tested in GCM experiments.

The single-column model used in this study evolved from the one described by Iacobellis and Somerville (1991a,b). The SCM is a computationally efficient and economical one-dimensional (vertical) model, resembling a single column of a general circulation model (GCM). The SCM contains the full set of parameterizations of subgrid physical processes that are normally found in a modern GCM. The SCM is applied at a specific site having a horizontal extent typical of a GCM grid cell. Since the model is one-dimensional, the advective terms in the budget equations are specified from observations, or from operational numerical weather prediction analyses.

The SCM is diagnostic rather than prognostic. Its input is an initial state, plus the time-dependent advection terms in the conservation equations, provided at all model layers. Its output is a complete heat and water budget for the study site, including temperature and moisture profiles, clouds and their radiative properties, diabatic heating terms, surface energy balance components, and hydrologic cycle elements, all specified as functions of time. For a more complete discussion of SCMs, see Randall et al. (1996) and Iacobellis and Somerville (1991a,b).

A typical configuration of the SCM has 16 vertical layers in the atmosphere and either a land surface scheme with a surface energy balance calculation or an underlying ocean mixed layer model. The standard version of the SCM uses a time step of 7.5 minutes. A diurnally varying solar signal dependent on the latitude and time of year is applied at the top of the model atmosphere. The standard SCM uses the longwave radiation parameterization of Morcrette (1990) and the solar radiation parameterization of Fouquart and Bonnel (1980). The model is coded in a modular manner, however, and so alternative radiation packages can be substituted for the standard ones. The ocean mixed layer model is that of

Price et al. (1986), and the surface heat fluxes over the ocean are determined using the parameterization developed for TOGA-COARE (Fairall et al., 1996). Typical results (from applying the SCM to TOGA-COARE data) are given below and in Lee et al. (1997).

A variety of parameterizations representing cumulus convection, cloud prognostication, and cloud radiative properties were tested in this study and used for intercomparison with those of the GSFC GCM. The cumulus convection parameterizations include those of Kuo (1974) (as modified by Anthes, 1977) and of Arakawa and Schubert (1974) (with downdrafts as specified by Kao and Ogura, 1987), including the relaxed version used in the GSFC GCM, and of Emanuel (1991). The cloud prediction schemes are those of Slingo (1987), Smith (1990) and Sundqvist et al. (1989). The cloud radiative properties are specified from either McFarlane et al. (1992) or a combination of Stephens (1977) (water clouds) and Suzuki and Tanaka (1993) (ice clouds). Cloud liquid water is a prognostic model variable when the Smith or Sundqvist scheme is active, but not when the Slingo routine is being used. These parameterizations are switch-selectable in the model.

2. Papers published with support from this grant

Iacobellis, S. F., R. Frouin, H. Razafimpanilo and R. C. J. Somerville, 1994: North African savanna fires and atmospheric carbon dioxide. *Journal of Geophysical Research*, **99**, D4, 8321-8334.

Waliser, D. E., and R. C. J. Somerville, 1994: The preferred latitudes of the intertropical convergence zone. *Journal of the Atmospheric Sciences*, **51**, 1619-1639.

Razafimpanilo, H., R. Frouin, S. F. Iacobellis, and R. C. J. Somerville, 1995: Methodology for estimating burned area from AVHRR reflectance data. *Remote Sensing of Environment*, **54**, 273-289.

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Soloviev, G. I., V. D. Shapiro, R. C. J. Somerville and B. Shkoller, 1996: The tilting instability in a two-dimensional viscous fluid. *Journal of the Atmospheric Sciences*, **53**, 2671-2684.

Lee, W.-H., and R. C. J. Somerville, 1996: Effects of alternative cloud radiation parameterizations in a general circulation model. *Annalae Geophysicae*, **14**, 107-114.

Byrne, R. N., R. C. J. Somerville and B. Subasilar, 1996: Broken-cloud enhancement of solar radiation absorption. *Journal of the Atmospheric Sciences*, **53**, 878-886.

Somerville, R. C. J., S. F. Iacobellis and W.-H. Lee, 1996: Effects of cloud-radiation schemes on climate model results. *World Resource Review*, **8**, 321-333.

Randall, D. A., K.-M. Xu, R. C. J. Somerville and S. Iacobellis, 1996: Single-column models and cloud ensemble models as links between observations and climate models. *Journal of Climate*, **9**, 1683-1697.

Lee, W.-H., S. F. Iacobellis, and R. C. J. Somerville, 1997: Cloud-radiation forcings and feedbacks: General circulation model tests and observational validation. *Journal of Climate*, **10**, 2479-2496.

3. TOGA-COARE results from this grant

We now present sample results of applying the single-column model (SCM) to TOGA-COARE data. We may also envision TOGA-COARE as a prototype for the ARM Tropical Western Pacific (TWP) site. One goal of this work was to determine how well typical GCM parameterizations of cumulus convection and cloud liquid water do at simulating relevant atmospheric properties in the TWP region during the Intensive Observing Period (IOP) of COARE. We also wished to determine whether we could use sounding data on the boundary of the COARE Intensive Flux Array (IFA) to provide boundary forcing. One major result of our work is that soundings on the COARE Intensive Flux Array (IFA) boundary are sufficiently accurate for this purpose. Earlier SCM work had used operational numerical weather prediction (NWP) analyses to provide the advective constraint, but this option has the disadvantage that the parameterizations in the NWP model can potentially influence the SCM. In the results presented below, both types of boundary forcing are used. Surface and satellite radiation measurements were used to provide an initial evaluation of the performance of the different parameterizations. The results of this evaluation were then used to develop a preliminary optimized prognostic cloud scheme for the region.

The configuration of the SCM used in the following experiments has 16 vertical layers in the atmosphere and an underlying ocean mixed layer model (Price et al., 1986). The SCM uses a timestep of 7.5 minutes. The albedo of the ocean surface is set constant at 0.05. A diurnally varying solar signal dependent on the latitude and time of year is applied at the top of the model atmosphere. The solar constant is set to 1370 W m^{-2} . The SCM experiments in this study use the longwave radiation parameterization of Morcrette (1990) and the solar radiation parameterization of Fouquart and Bonnel (1980). The surface heat fluxes are determined using the parameterization developed for TOGA-COARE by Fairall et al. (1996).

A variety of parameterizations representing cumulus convection, cloud prognostication, and cloud radiative properties have been used in this study. The cumulus convection parameterizations are those of Kuo (1974) (as modified by Anthes, 1977), Arakawa and Schubert (1974) (with downdrafts as specified by Kao and Ogura, 1987), and Emanuel (1991). The cloud prediction schemes are Slingo (1987), Smith (1990) and Sundqvist et al. (1989). The cloud radiative properties are specified from either McFarlane et al. (1992) or a combination of Stephens (1978) (water clouds) and Suzuki and Tanaka (1993) (ice clouds). Cloud liquid water is a prognostic model variable when the Smith or Sundqvist scheme is used, but not when the Slingo routine is used.

We first present a series of seven "long-term" experiments. The model configuration in each experiment differs only in the specification of the cumulus convection parameterization, the cloud prognostication scheme and/or the parameterization of cloud-radiative properties. The parameterizations used in each experiment are shown in Table 1.

In each experiment, the SCM was applied at $19 \text{ } 5^\circ \times 5^\circ$ sites within the bounded region of the western tropical Pacific extending from 137.5°E - 172.5°E and 7.5°N - 7.5°S . The size and location of the individual sites was selected to coincide with the ECMWF operational analysis data which is used as model forcing in these experiments. Each experiment extends from 01 Nov 1992 to 28 Feb 1993 which corresponds to the IOP of

Table 2. Cloud Forcing and Radiative Results

Exp. No.	CF _{SW} (W m ⁻²)	CF _{LW} (W m ⁻²)	CF (W m ⁻²)	Albedo	OLR (W m ⁻²)	Insol. (W m ⁻²)
1	-100	56	-44	0.33	236	200
2	-101	57	-44	0.33	229	199
3	-108	65	-43	0.35	224	191
4	-121	66	-55	0.38	225	176
5	-137	76	-61	0.42	210	159
6	-144	82	-62	0.44	207	151
7	-138	71	-67	0.42	220	154
GMS	-108	62	-46	0.37	228	---

1993 to 28 Feb 1993. These 30 runs were repeated at each of the 19 5°x 5° sites. Long-term regional means during the TOGA-COARE IOP are formed by averaging results from the 570 (19 sites x 30 4-day periods) model runs for each configuration of model parameterizations.

The cloud radiative forcing terms (Senior and Mitchell, 1993) and other cloud-

Table 1. Model Configurations

Exp. No.	Cumulus Convection	Cloud Scheme	Cloud-Radiative Properties
1	Kuo-Anthes	Slingo	McFarlane
2	Emanuel	Slingo	McFarlane
3	Arakawa-Schubert	Slingo	McFarlane
4	Kuo-Anthes	Smith	Stephens+Suzuki
5	Emanuel	Smith	Stephens+Suzuki
6	Arakawa-Schubert	Smith	Stephens+Suzuki
7	Kuo-Anthes	Sundqvist	Stephens+Suzuki

TOGA-COARE. At each site the model was initialized at 01 Nov 1992 00LST and run for a period of four days. The model was then reinitialized and run again for the next four days. This process was repeated a total of 30 times with the last 4-day run extending from 25 Feb

radiation variables produced by the these SCM experiments are examined to understand how the various parameterizations may affect the modeled climatological heat budget of the TOGA-COARE region. The cloud radiative forcing represents the extra amount of radiation that is either emitted to space or absorbed by the earth-atmosphere system due to the presence of clouds. The

total cloud forcing (CF) is composed of a shortwave component (SW_{CF}) and a longwave component (LW_{CF}), as follows:

$$CF = CF_{SW} + CF_{LW} = (Q - Q_c) - (F - F_c)$$

where Q is the net incoming solar radiation, F is the outgoing longwave radiation and the subscript c indicates clear-sky fluxes. If CF is positive then the clouds have a warming effect on the earth-atmosphere system. These terms averaged over all 19 sites and over the 4 month time period for each of the seven SCM experiments are shown in Table 2. The last row of Table 2 contains the observed values obtained from GMS-4 satellite measurements.

These results show that when the Slingo cloud scheme is used (experiments 1-3) model averages of CF_{SW}, CF_{LW}, OLR, albedo and insolation are less sensitive to the choice of cumulus parameterization than when the Smith cloud scheme is employed (experiments 4-6). The effect of the treatment of cloud liquid water can be seen by comparing the results from experiments 1, 4 and 7. Here the Kuo-Anthes convection was used in each case while the cloud prognostication scheme varied. The model results show large decreases in insolation and OLR and large increases (in magnitude) in albedo and both the shortwave and longwave cloud forcing terms for experiments 4 and 7 compared to experiment 1.

The model results are much closer to the observed GMS-4 values when cloud liquid water is not an interactive variable (experiments 1-3). The larger absolute values of the cloud forcing terms, the increase in albedo, and the decrease in OLR and insolation in experiments 4-7, all indicate that the model is over-estimating the cloud fraction and/or the cloud optical thickness when cloud liquid water is an interactive variable.

The SCM was next applied over the site of the Intensive Flux Array (IFA). In this series of experiments the horizontal advection terms necessary to force the SCM are derived from sounding measurements taken along the perimeter of the IFA. Thus, direct observations are used to force the model in these experiments as opposed to model assimilation products. The SCM was run for several 5-day periods within the TOGA-COARE IOP of 01Nov92 - 28Feb93 using model configuration #7 (see Table 1).

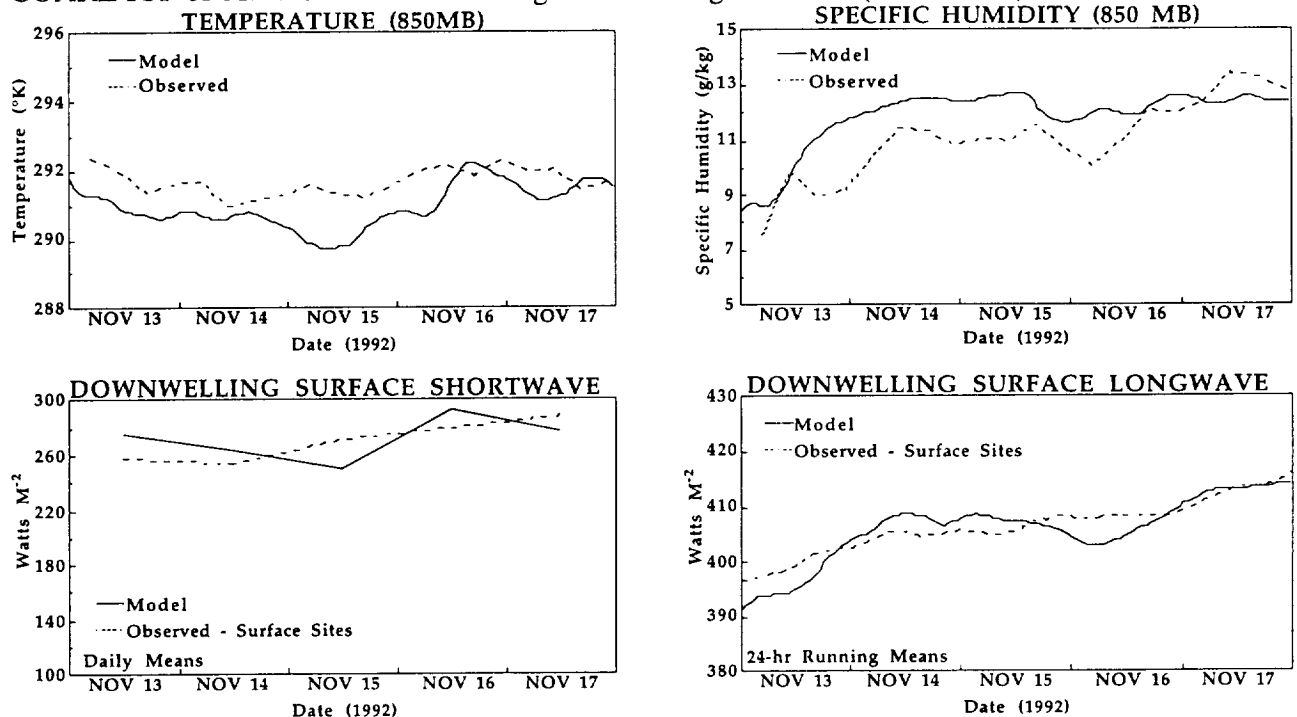


Figure 1.

Figure 1 shows results that typify the SCM response during low precipitation conditions over the IFA. During these 'dry' events, the SCM typically reproduced the observed temperature and humidity evolution and produced diagnostic radiative quantities that compared very well to both surface and satellite measurements. SCM results from a 5-day period that experienced significant precipitation are shown in Figure 2. During these 'wet' events the SCM often underestimated the surface downwelling solar radiation and overestimated the planetary albedo while reproducing reasonably well the precipitation as measured by the satellite measurements of the Microwave Sounding Unit (MSU).

These model results from the IFA site are consistent with the long-term runs discussed above in that they both indicate the model parameterizations are over-estimating the cloudiness and/or cloud optical thickness. Further analysis of the model results indicates that very large errors in cloud optical thickness would be necessary solely to explain the model discrepancies in albedo and surface shortwave. Thus, overestimation of the fractional cloud coverage is more likely to be the cause of the majority of the errors in

albedo and surface shortwave. The fractional cloud cover for convective clouds in the Sundqvist cloud scheme is given by:

$$CLD = \xi \tau (1 + RH) (1 + (\sigma_b - \sigma_t)/A) / (1 + B \xi \tau)$$

where CLD is fractional cloud amount, RH is relative humidity, σ_b , σ_t are the sigma level of cloud base and cloud top, ξ is a quantity from the Kuo convection scheme proportional to the moisture convergence, τ is a convective time scale and A, B are constants. In Sundqvist's scheme, the values of A and B are set to 0.3 and 2.5 respectively. We performed numerous SCM runs in the IFA region throughout the IOP period, each run with different values of A and B. A comparison of model albedo and surface shortwave to observations yielded "optimized" values of A and B of approximately 0.5 and 4.0.

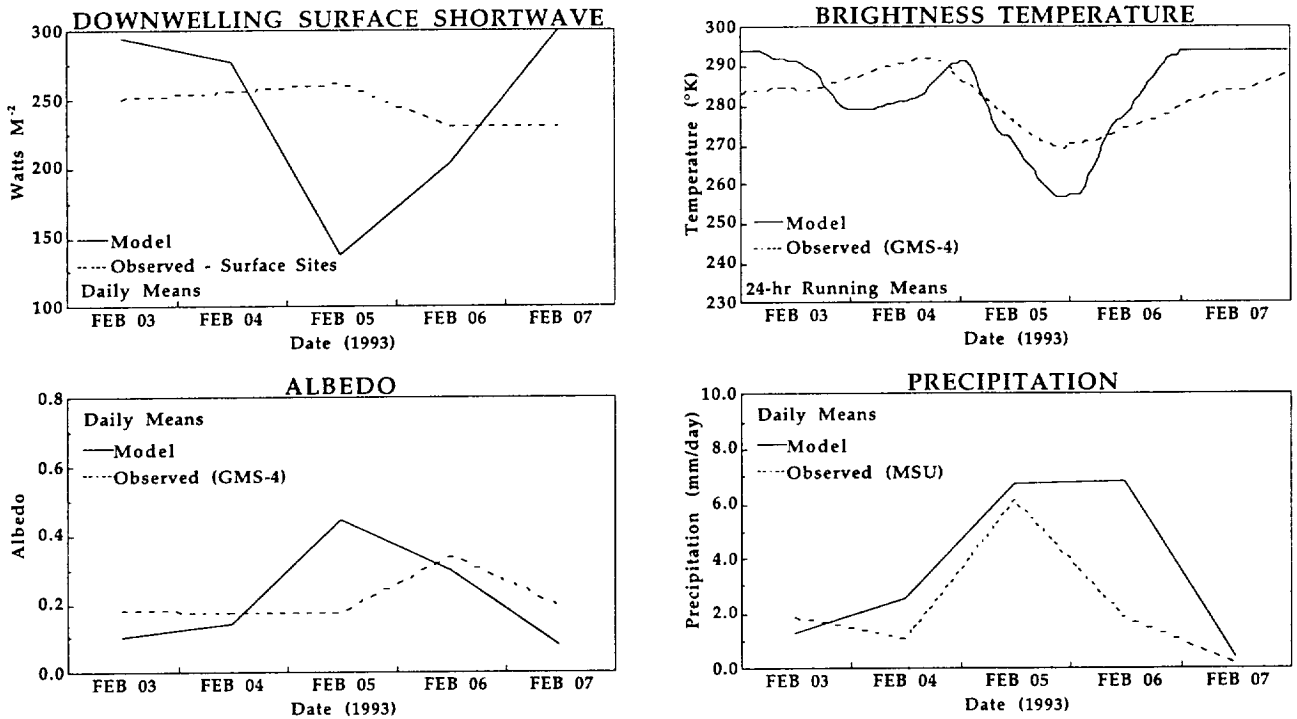


Figure 2.

The use of these optimized values of A and B improves the SCM estimates of albedo and downwelling shortwave radiation during precipitation events in the IFA region. A further and more substantial test of this optimization was performed by rerunning the long-term runs (SCM in configuration 7) with the optimized values of A and B. The model results from the "optimized" run and the original run are shown below in Table 3, along with measured values from the GMS-4 satellite. The results from the SCM run using the optimized values of A and B show a clear improvement over the original run when compared to

Table 3. Original vs. Optimized

	CF _{SW} ($W m^{-2}$)	CF _{LW} ($W m^{-2}$)	CF ($W m^{-2}$)	Albedo	OLR ($W m^{-2}$)	Insol. ($W m^{-2}$)
Original	-138	71	-67	0.42	220	154
Optimized	-112	59	-53	0.36	232	183
GMS	-108	62	-46	0.37	228	---

measurements taken during the TOGA-COARE IOP.

These illustrative results have

shown that the SCM can be forced with direct observations of the horizontal advection terms, based on soundings on the COARE IFA boundary, rather than with estimates from inevitably model-dependent objective analyses, and can still produce realistic budgets, as confirmed by both surface and satellite measurements. The sensitivity test performed here with the "optimized" values of A and B is admittedly simple, and more rigorous analyses will be needed to yield a satisfactory and physically consistent cloud prognostication scheme for the western tropical Pacific. However, this illustrative study demonstrates the potential of the SCM as a useful and economical tool in parameterization development.

3. References

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Shyh-Chin Chen and John O. Roads Activities

a. A manuscript dealing with some aspects of the U.S. hydrologic cycle was published in the AMS Bulletin (Roads et al., 1994). In this work we described a large-scale, grid point, atmospheric, hydrologic precipitation, atmospheric moisture flux convergence, and a residual evaporation for the coterminous United States. We also described a large-scale, basin, hydrologic climatology of the same atmospheric variables as well as residual surface water and streamflow divergence or runoff for various large-scale river basins terminating at the United States boundary. Climatologically, precipitation, which had a United States annual mean of more than 2.1 mm/day, was largely balanced by evaporation; atmospheric moisture flux convergence was also an important contributor (about .5 mm/day), especially during the wintertime, and especially along the United States West Coast. At the surface, seasonal and anomalous surface water (including snow) variations on the order of 10 cm/year, were forced by seasonal variations of about one mm/day in atmospheric moisture flux convergence (precipitation minus evaporation) and streamflow divergence. The strongest seasonal variations were found along the United States West Coast. Unlike the climatological means and seasonal variations, atmospheric precipitation anomalies were best related to atmospheric moisture flux convergence anomalies and less well related to the residual evaporation anomalies. Streamflow divergence anomalies were also related to the atmospheric moisture flux convergence anomalies, especially at lags of around 15 days. A better lag relationship occurred between streamflow divergence and precipitation anomalies.

1. Roads et al. (1994b, 1995a, 1995b) compared the National Meteorological Center's (NMC's) twice-daily, global 2.5° pressure analyses of temperature, relative humidity and wind speed, over the coterminous U.S., to the National Climatic Data Center's (NCDC's) twice daily, upper-air radiosonde observations and hourly, first-order, surface observations for the period Jan. 1, 1988-Dec. 31, 1992. NMC's analyses have clearly improved during this time period. Still, there are some noticeable differences, especially near the surface and especially at 12 UTC. During the early morning there is a warm bias, relative humidity is too low, and the surface wind speed is too strong. Weaker systematic errors occur during the late afternoon; there is a cold bias; relative humidity is too high and the surface wind speed is still too strong. Aloft, the bias is noticeably reduced, except for the wind speed which is somewhat too weak. The analysis wind speed also has too strong temporal variations near the surface and too weak temporal variations aloft. We can correct for the analysis climatology at each station by removing the bias. We can further correct transient variations simply by multiplying the analysis anomalies by the ratio of the station standard deviation to the analysis standard deviation. Correcting for the biases and variances and spatially interpolating the analysis and station corrections to a .5° grid provides a useful guess for local conditions, especially if there is not a surface or radiosonde station within about 200 km.

c. Norris et al. (1995) compared six SSM/I PW algorithms with a large radiosonde dataset and with atmospheric analyses over the ocean. Several of the algorithms provided a good linear fit over a wide range of values. A few of the algorithms, however, were found to report PW values which were biased. These differences could introduce significant systematic errors to subsequent analyses based on SSM/I PW. To augment our oceanic PW

data, we then derived a statistical fit between SSM/I microwave radiances and PW calculated from NMC analysis for several years over both land and ocean. Although the errors are clearly larger over the land regions, the errors are still smaller than the signal. Through appropriate corrections and statistical filters, we may be able to eventually derive a useful global PW.

d. Chen et al. (1996) described how the atmospheric hydrologic budget in an idealized general circulation model is difficult to balance, especially if samples are too infrequent, mainly because of an inaccurately determined moisture flux divergence. As we increase the skill of the moisture convergence calculation by increasing the sample frequency, the importance of the perceptible water tendency also becomes more apparent in short-term budgets. Current NMC atmospheric hydrologic pressure analyses of moisture fluxes and even satellite SSM/I microwave liquid water measurements may have similar sampling problems. Modern analyses should provide more frequently sampled or even continuously accumulated hydrologic quantities, just as precipitation is currently provided.

e. Roads et al. (1996a) investigated the climatic response to six equilibrium CO₂ concentrations-200, 265, 330 (present day concentration or control), 460, 660, and 1000ppm. The largest relative changes from the present day climate occur at low CO₂ amounts and low temperatures; climatic changes are relatively smaller at high CO₂ amounts. In fact, CCM1 was potentially unstable to substantial decreases in CO₂. Temperature, perceptible water, evaporation, and precipitation, increased with increasing CO₂. Snow decreased with increasing CO₂. Soil moisture had a more complicated seasonal dependence. Annually averaged, soil moisture changed little as the equilibrium CO₂ changed. During the spring and early summer months, soil moisture decreased with increasing CO₂ over most northern hemisphere land regions. This desiccation results in part from decreased snow cover and decreased precipitation. Soil moisture then increased during the fall and winter as the precipitation increased and the snow cover decreased.

f. Roads et al. (1996b, c; 1997) presented further details of the large-scale hydrologic and energy cycles from a version of NCEP's global spectral model (GSM) used for NCEP's global reanalysis. The model's vertical domain is 18 sigma layers (19 levels, which includes the surface and the model top at 0 pressure). A T62 (192x94) 2o grid is used in the horizontal. We have been continuously integrating the GSM with periodic updates of the sea surface temperatures, sea ice and also have set limits upon the snow accumulations (snow is always less than 50 m) in high latitudes. We have also developed a complete diagnostic package for the vertically integrated as well as 3-dimensional water and energy cycles. All water and energy terms are accumulated every time step.

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